Strategies for Environmental Monitoring
of Marine Carbon Capture and Storage

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Presentation programme and abstracts



Oral presentations

Day	Time	Session	Room	Author	Title
Monday 22 October 2018	14:00 - 15:40	2F Environmental impacts & remediation	Eureka 2	Steve Widdicombe et al.	Establishing and effective environmental baseline for offshore CCS
Tuesday 23 October 2018	11:20 - 13:00	5F Monitoring: Separating signal from noise in the environment	Eureka 2	Jerry Blackford et al.	Ensuring efficient and robust storage - the role of marine system modelling
Tuesday 23 October 2018	16:00 - 17:40	6F Monitoring: Novel tools and challenging settings	Eureka 2	Matt Mowlem et al.	Biogeochemical sensors for offshore CCS reservoir integrity verification
Thursday 25 October 2018	09:10 - 10:50	10F Geochemical modelling	Eureka 2	Pierre Cazenave et al.	Regional modelling to inform the design of sub-sea CO_2 storage monitoring networks
Thursday 25 October 2018	09:10 - 10:50	10F Geochemical modelling	Eureka 2	Kristian Gunderson et al.	Combining models and machine learning techniques to design leak detection monitoring

Poster presentations

Day	Time	Session	Room	Author	Title
Tuesday 23 October 2018	14:00 - 16:00	Poster Session A - board 209	Exhibition hall	Anna Oleynik et al.	Simplified modelling as a tool to locate and quantify fluxes from a CO_2 seep to marine waters
Tuesday 23 October 2018	14:00 - 16:00	Poster Session A - board 249	Exhibition hall	A. Omar et al.	Cseep as a stoichiometric tool todistinguish a seep signal from the natural variability
Tuesday 23 October 2018	14:00 - 16:00	Poster Session A - board 219	Exhibition hall	Umer Saleem et al.	Numerical modelling of CO_2 flow through sediments into water column
Weds 24 October 2018	14:00 - 16:00	Poster Session B - board 292	Exhibition hall	Jon Bull et al.	Constraining leakage pathways through the overburden above sub-seafloor CO_2 storage reservoirs
Weds 24 October 2018	14:00 - 16:00	Poster Session B - board 218	Exhibition hall	Marcus Dewar et al.	Prediction of greenhouse gas leakages from potential North Sea storage sites into coastal waters by an unstructured, multi-scale and multi-phase flow model
Weds 24 October 2018	14:00 - 16:00	Poster Session B - board 220	Exhibition hall	Gennadi Lessin et al.	Can we use departure from natural covariance relationships for monitoring of offshore carbon storage integrity?

Ensuring efficient and robust offshore storage – the role of marine system modelling

Jerry Blackford[a *], Guttorm Alendal[b], Yuri Artioli[a], Helge Avlesen[c], Pierre W. Cazenave[a], Baixin Chen[d], Andrew W. Dale[e], Marius Dewar[d], Maribel I. García-Ibáñez[c], Jonas Gros[e], Kristian Gundersen[b], Matthias Haeckel[e], Sorush Khajepor[d], Gennadi Lessin[a], Anna Oleynik[b], Abdirahman M. Omar[c],Umer Saleem[d]

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This paper describes the utility of developing marine system models to aid the efficient and regulatory compliant development of offshore carbon storage, maximising containment assurance by well-planned monitoring strategies. Using examples from several model systems, we show that marine models allow us to characterize the chemical perturbations arising from hypothetical release scenarios whilst concurrently quantifying the natural variability of the system with respect to the same chemical signatures. Consequently models can identify a range of potential leakage anomaly detection criteria, identifying the most sensitive discriminators applicable to a given site or season. Further, using models as in-silico testbeds we can devise the most cost-efficient deployment of sensors to maximise detection of CO_2 leakage. Modelling studies can also contribute to the required risk assessments, by quantifying potential impact from hypothetical release scenarios. Finally, given this demonstrable potential we discuss the challenges to ensuring model systems are available, fit for purpose and transferable to CCS operations across the globe.

Constraining the physical properties of chimney/pipe structures within sedimentary basins

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Evaluation of seismic reflection data has revealed structures cross-cutting the overburden within many sedimentary basins worldwide, including those in the North Sea and Norwegian Sea. These seismically-imaged pipes and chimneys are considered to be possible pathways for fluid flow. Natural fluids from deeper strata have migrated through these structures at some point in geological time. We test the hypothesis that many chimney and pipe structures imaged on seismic reflection profiles worldwide are the consequence of (1) a fracture network that has been reactivated by pore fluid pressure which facilitates the migration of fluids upwards; and (2) shallow sub-seafloor lateral migration of fluids along stratigraphic interfaces and near-surface fractures. An experimental approach to determine the physical properties of these structures beneath the sub-seafloor is described, with particular reference to an investigation of the Scanner Pockmark complex in the North Sea. The study is relevant to storage operators, policy-makers and those keen to demonstrate that it is possible to constrain and fully understand the physical properties and possible fluid flow pathways in the sedimentary overburden above sub-seafloor CO_2 storage reservoirs.

Regional modelling to inform the design of sub-sea CO_2 storage monitoring networks

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A 3D hydrodynamic model (FVCOM) coupled to a carbonate system (ERSEM) has been used to model a number of seabed CO_2 release scenarios ranging from 3 to 3000 t d^{-1} for the Goldeneye complex in the northern North Sea. The results of the scenario runs were used to characterise the fate of CO_2 in the water column in space and time. A new approach to designing monitoring networks has been implemented and compared with a simple approach. A weighted greedy set algorithm is used to identify the positions within the model domain which yield the greatest combined coverage for the smallest number of sampling stations, further limited by selecting only a feasible number of sample sites. The weighted greedy set algorithm incorporates the effect of the unstructured grid in FVCOM as well as the proximity of the candidate sample locations to the Goldeneye complex. For the range of release rates simulated, the design of the optimal sampling strategy changes depending on the magnitude of the release. The role of the tides discriminates the four release scenarios into two categories: for the lower release rates (3 and 30 t d^{-1}), the effect of the tide is relatively unimportant in the distribution; for the larger release rates (300 and 3000 t d^{-1}), the direction of the principal tidal axis controls the distribution of the sampling stations more strongly. Comparison of the weighted greedy set approach shows it is able to identify releases sooner and with a stronger signal than a simple regular sampling approach.

Prediction of greenhouse gas leakages from potential North Sea storage sites into coastal waters by an unstructured, multi-scale and multi-phase flow

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This paper reports the development of a multi-scale, multi-phase modules for bubble plume dynamics within the FVCOM numerical model to investigate the fate of CO_2 leakage into the water column from potential carbon storage sites. The model is capable of analysing the fluid dynamics, dissolution and leakage impacts, including seawater pH and pCO_2 changes, at scales ranging from the leakage site in the order of meters, up to the regional and coastal ocean scale in the order of thousands of kilometres for a wide range of leakage scenarios, from bubbly seeps to well blowouts. The developed model is tested to predict the fate of leakage of CO_2 from the Goldeneye area of the North Sea, a potential site for CO_2 storage. Results show that the bubble modules are successfully coupled with the ocean model and predicted, from 3 leakage ports within a 5x5 m^2 area at a rate of 0.3 Tons/day, the maximum increases of concentration of dissolved CO_2 (DIC) reaches to 0.03kg/m^3 at the leakage sites within an area of 2.5 km^2, with DIC increases of 0.01 kg/m^3 at a leakage time of 5 hours. The CO_2 bubble plume reaches to a steady state at the height of 13 m and moves with the ocean current horizontally within a 2.2 m in diameter. The DIC plume then further develops to an area of 93 km^2 within one day and circulates periodically around the leakage site with the tidal currents.

Ensuring efficient and robust offshore storage - use of models and machine learning techniques to design leak detection monitoring

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The use of machine learning techniques to identify CO_2 seeps to marine waters is assessed. These techniques require a large amount of data for training, here obtained through model predictions on how CO_2 seeps behave in the water column. Goldeneye, off the coast of Scotland, has been used as area of study. It is shown that Convolutional Neural Networks (CNN) are able to, with high confidence, to classify time series from the model simulations into leak and no-leak situations. CNN in data analysis can increase the detectability of CO_2 seeps, and thus the optimization of sensor deployment and monitoring design.

Can we use departure from natural co-variance relationships for monitoring of offshore carbon storage integrity?

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Carbon capture with offshore storage may take place at various geographical locations, characterized by diverse physical and biogeochemical properties and dynamics of the overlying water. In order to ensure storage integrity, baseline conditions must be carefully assessed for each potential storage area, which will allow design and deployment of optimal monitoring and sampling programs and establish appropriate site-specific criteria for anomaly detection, to allow timely reaction and necessary remedial measures.

Within this paper, we assess applicability of using outputs of coupled hydrodynamic-biogeochemical models for the selection of appropriate variables to describe baseline variability and, consequently, strategies for the following monitoring. Via application of multivariate linear regression we identify combinations of modelled variables that best predict variability in pCO_2 at a location corresponding to the potential storage site at Goldeneye Field in the Central North Sea. Although some variable pairs better predict pCO_2 variability, we focus on a combination of oxygen saturation and silicate, as variables that can potentially be frequently and accurately monitored over long periods. In this work we employ highly simplified leakage scenarios to highlight the accuracy of baseline characterization and implications for establishment of thresholds for anomaly detection in highly dynamic marine environments. We conclude that hydrodynamic-biogeochemical models are invaluable tools for informing cost-effective monitoring strategies regarding the optimal number and combination of parameters surveyed and for establishing appropriate anomaly criteria for each potential storage location.

Biogeochemical sensors for offshore CCS reservoir integrity verification

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Monitoring for biogeochemical changes in marine systems will provide an important additional monitoring approach with high sensitivity, is independent of bubble formation and provides an ability to verify fluid flows as CO_2 which acoustic technics cannot. Here we present recent advances in both biogeochemical sensor technology for CCS reservoir integrity verification and understanding of the analytical performance and data manipulation required for detection and quantification of suspected leaks. Advances include: the first generation of reagent based chemical analysers with sufficient performance for CCS applications that can measure pH, nitrate and phosphate and can be deployed on low-power autonomous vehicles; new optodes for Oxygen and pH; and novel estimation of benthic dissolved inorganic carbon fluxes using i) eddy covariance and fast O_2 and pH sensors; or ii) chemical gradients in the turbulent boundary layer. We also outline a roadmap for development of further technologies including sediment profiling systems and sensors for total alkalinity and dissolved inorganic carbon.

Simplified modeling as a tool to locate and quantify fluxes from CO_2 seep to marine waters

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An adequate monitoring program will be an intrinsic part of all CO_2 storage projects, as required by regulations. This program must involve a surface monitoring component in addition to the subsurface methods. Should anomaly be detected, the monitoring program enters the costly confirmation modus, i.e., surveys to localize or dispel suspicion of an ongoing seep. Inverse methods applied to the tracer transport equation, using proper current statistics, are demonstrated here as a valuable tool to make predictions on where a seep might be located, and the flux associated with the source. The framework can be updated as new measurements are being collected.

The stoichiometric C_{seep} method as a tool to distinguish CO_2 seepage signal from the natural variability

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For CO_2 Capture and Storage (CCS) technologies to be classified as a climate change mitigation option, an efficient, safe and enduring storage needs to be verified through site-specific monitoring programs, which is required by the international and national regulations. In the case of offshore geological storage, the high spatiotemporal natural variability of seawater CO_2 hampers the interpretation of a seepage signal. Therefore, the characterization of the spatiotemporal natural variability of seawater CO_2 through baseline studies is required when designing an efficient monitoring program.

Here we present a stoichiometric method called C_{seep} for the determination of excess seeped CO_2 dissolved in the water column. The method takes advantage of the fact that the production and consumption of seawater CO_2 by natural process can be predicted from variables that are not impacted by CO_2 seepage. For instance, biological production of CO_2 is always associated with a certain amount of oxygen consumption and nutrient production while CO_2 seepage has no specific effect on oxygen and nutrient levels in seawater. We discuss the applicability of the C_{seep} method as an offshore CCS monitoring tool around the Goldeneye area – a potential offshore CCS site in the Northern North Sea. We also evaluate how the choice of measured parameters influences the sensitivity/accuracy of the C_{seep} calculations. The results (partly preliminary) show that the C_{seep} method clearly minimizes the effect of natural variability on seawater DIC measurements while highlighting the simulated seepage signal. Moreover, C_{seep} values computed using data achievable with autonomous sensors can have an uncertainty similar to C_{seep} values obtained with highly accurate benchtop instrumentation, implying that the method can be fully automated.

Numerical modelling of gases flow through sediments into water column

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Carbon capture and storage (CCS), among the proposed mitigation strategies, has been considered as one of options to mitigate the global warming. While, the potential leakage of CO_2 from the undersea bed storage sites could have adverse effects on processes in and around sediments. Steps to detect and monitor leakage of CO_2, therefore, must be developed to support commercial scale sub-seabed carbon capture and storage. This research focuses on the development of a numerical model to predict the characteristics of migration of CO_2 through superimposing sediments and residues in seabed, in extension of an effort to enhance the understanding of CO_2 behavior of leaked gas from a storage site. As the first stage, a two-phase flow model is developed with basis on Navier-Stokes-Darcy equations to simulate the dynamics of leaked undissolved gases flow through the sediments into the turbulent bottom boundary layer of the ocean. The developed model is preliminarily tested to simulate the undissolved gas dispersion in 2-D sediments. The results shown that the structure of sediments plays a key role on the gas dispersion, the gas breakthrough a 3.5 m sediment with connected fractures is about 4 times faster than through those without fractures and with non-connected fractures. The simulation results also show that the ocean current affects slightly the gas plume development in sediments in both the plume structure and the breakthrough times. The model will be further extended in the next stage to a model of CO_2 liquid/gas (including dissolution) dispersion and dissolution through sediments into turbulent ocean.

Establishing an effective environmental baseline for offshore CCS

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The proposed storage of CO_2 in sub-seabed geological reservoirs, known as Carbon dioxide Capture and Storage (CCS), could make a practical and significant contribution to reducing atmospheric CO_2 emissions thereby alleviating environmental and ecological damage due to climate change and ocean acidification. However, before any new marine activity is conducted, it is standard procedure for any environmental risks potentially posed by that activity to be considered. In particular, understanding what is 'natural' or 'normal' for an area is essential when looking to establish criteria against which potential environmental impacts can be identified, monitored and quantified. To that end, all offshore CCS projects would benefit from constructing an effective environmental baseline prior to the start of storage. However, due to the large spatial extent of storage complexes and the expectation that storage of the CO_2 will be permanent, there are a number of financial, logistical and methodological issues associated with constructing such baselines.

Firstly, sub-seabed storage complexes are sizeable structures. Whilst individual leakage events themselves are likely to be rare and have a small spatial impact, it might be considered that anywhere above the storage complex could potentially be the location of a leakage event. In reality very few areas will be at any risk from leakage but for the sake of public reassurance and in line with the precautionary principle, constructing an environmental baseline which covered the whole complex footprint would be prudent. However, assessing such large areas does raise certain challenges. The marine environment in general is highly spatially variable in terms of its physical, chemical and biological makeup with scales of variability ranging from the sub-metre scale corresponding to benthic patchiness, to dynamic boundaries between water masses of different origins, which may stretch for many kilometres. Consequently, the large area of marine environment that sits above a CCS reservoir will inevitably contain a mosaic of different seabed habitats and biological communities. It will also consist of varying water masses and pelagic biomes. This large spatial extent and high level of spatial variability, raises problems of affordability when attempting to construct the type of environmental baseline required to comprehensively assess any potential environmental risks associated with CCS activities.

In addition to the problems associated with assessing environmental heterogeneity over large spatial scales, described above, the marine environment also displays high levels of temporal variability. This is particularly relevant to many of the environmental parameters that may be directly used to identify and monitor CO2 leakage events, such as changes in carbonate chemistry parameters which can undergo large and rapid fluctuations as a result of naturally occurring biological and physical processes. In addition to shorter term fluctuations, the marine environment is being exposed to longer-term changes in environmental conditions driven by man-made pressures such as climate change and changes in human activities (e.g. fishing, resource extraction, pollution). These gradual, chronic changes are especially important when considering the typical life-span of a CCS project. With the intention of storing CO_2 permanently it is essential that future long-term changes in environmental conditions are understood and such changes are not falsely attributed to CCS activities. All of this means that collecting sufficient amounts of observational data to adequately account for tidal, seasonal, annual and decadal trends and cycles, prior to starting any CCS activities would be impractical using traditional methods and would delay the rapid deployment of CCS projects, thus reducing this technology's potential contribution to reducing CO_2 emissions.

To meet the challenges of constructing effective environmental baselines that adequately account for large spatial and temporal scales, and thereby provide public reassurance that any potential risks are both identified and managed, new approaches in baseline data collection and analysis are needed. In this paper we illustrate a generic framework that combines some new and existing approaches and opportunities to extend environmental baselines through time and expand their spatial coverage. In doing so we illustrate how baseline data can be collected in a cost-effective and appropriate manner.